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MULTICHIP VERTICAL-EXTERNAL-CAVITY SURFACE-EMITTING LASERS: A COHERENT POWER SCALING SCHEME (POSTPRINT)

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14. ABSTRACT

We propose an efficient coherent power scaling scheme, the multichip vertical-external-cavity surface-emitting laser (VECSEL), in which the waste heat generated in the active region is distributed on multi-VECSEL chips such that the pump level at the thermal rollover is significantly increased. The advantages of this laser are discussed, and the development and demonstration of a two-chip VECSEL operating around 970 nm with over 19 W of output power is presented.

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Multichip vertical-external-cavity surface-emitting lasers: a coherent power scaling scheme

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We propose an efficient coherent power scaling scheme, the multichip vertical-external-cavity surface-emitting laser (VECSEL), in which the waste heat generated in the active region is distributed on multi-VECSEL chips such that the pump level at the thermal rollover is significantly increased. The advantages of this laser are discussed, and the development and demonstration of a two-chip VECSEL operating around 970 nm with over 19 W of output power is presented. © 2006 Optical Society of America

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Optically pumped semiconductor vertical-external-cavity surface-emitting lasers (VECSELs) are attractive owing to their high power, excellent beam quality, and large wavelength tunability.[1] However, the heating in the active region results in the thermal rollover and shut-off,[2] limiting their output power. Traditional power scaling of the VECSEL is based on increasing the pump spot size and keeping the pump irradiance constant. However, recent research pointed out that amplified spontaneous emission in the epitaxial plane is another major power-limiting mechanism in VECSELs, especially for a large pump spot.[3] A larger pump spot also introduces more diffraction loss due to the surface roughness of the processed VECSEL chip, increasing the threshold and decreasing the slope efficiency of the laser.[4] In addition, due to local quantum-well width fluctuations and composition fluctuations, as well as defects, more crystal inhomogenities may appear in a larger pump area, resulting in inhomogeneous broadening of the VECSEL[5]; that is, large spectral linewidth.[1]

Laser beam combining is an effective way to achieve power scaling of the laser. Spectral beam combining (SBC) of VECSELs by using volume Bragg gratings[6] can maintain near-diffraction-limited beam quality, but the combined output is an incoherent multiwavelength beam. Coherent beam combining (CBC) provides coherent power scaling with extremely high far-field intensity. However, each combined laser is forced to operate at the same frequency and is phase locked by master–slave coupling and self-feedback.[7] In addition, the coupling loss in the combining cascade structure decreases the efficiency of CBC.[8] Therefore it is not easy to maintain high efficiency CBC of lasers.

Here we propose and demonstrate an efficient coherent power-scaling approach, the multichip VECSEL, in which antireflection (AR)-coated VECSEL chips serve as folding mirrors in a zigzag fold cavity such as the W-shaped cavity. Recently we studied the functions of the AR-coated VECSEL chip serving as a folding mirror in a folded cavity[1,9] and found that if the folding angle within the VECSEL chip is very small, the VECSEL chip can provide not only resonant periodic gain (RPG), but also double the round-trip small-signal gain and eliminate the microcavity resonance for the VECSEL. Compared with the single-chip VECSEL, this multichip VECSEL has several potential advantages. (1) The heating is distributed on various VECSEL chips instead of a single chip. The thermal rollover is delayed, since less pump power on each chip will be needed for achieving a high-power VECSEL. Thus more pump power can be launched to the laser to achieve higher-power scaling than that of the single-chip VECSEL. (2) The multichip VECSEL has a much higher round-trip small-signal gain than a single-chip VECSEL. As a result, we can use an output coupler with low reflectance to increase the slope efficiency of the laser. (3) The output of a multichip VECSEL is a stable coherent beam with good beam quality that is easily controlled by the fold cavity. In this Letter, we
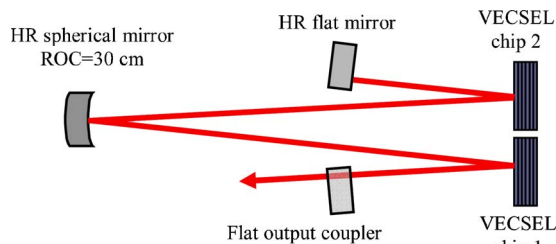
Fig. 1.   (Color online) Schematic of a two-chip VECSEL with a symmetric W-shaped cavity. Relative dimensions not to scale. HR, highly reflective.

present the development and demonstration of a two-chip VECSEL operating around 970 nm to prove the concept of the multichip VECSEL.

In the experiment two slightly different VECSEL chips are used. They are designed for emission around 975 nm and grown by metal–organic vapor phase epitaxy on an undoped GaAs substrate. Active regions of VECSEL chip 1 and VECSEL chip 2 consist of 14 and 10 InGaAs compressive strained quantum wells, respectively. Each quantum well is 8 nm thick and surrounded by GaAsP strain compensation layers and AlGaAs pump-absorbing barriers. The thickness and composition of the layers are optimized such that each quantum well is positioned at an antinode of the cavity standing wave to provide RPG. A high-reflecting ($R > 99.9\%$) distributed Bragg reflector (DBR) stack made of 25 pairs of AlGaAs/AlAs is grown on the top of the active region. In addition to the RPG active region and DBR stack, there is a high aluminum concentration AlGaAs etch-stop layer between the active region and the substrate to facilitate selective chemical substrate removal. The epitaxial side of the VECSEL wafer is mounted on chemical vapor deposition (CVD) diamond by indium solder. After the removal of the GaAs substrate and etch-stop layer, a single-layer Si_3N_4 ($n = 1.78$ at 980 nm) quarter-wave low-reflection coating (for a 975 nm signal) is deposited on the surface of the VECSEL chip to achieve a reflectivity of less than 1% at the signal wavelength and $\sim 3\%$ at 808 nm pump wavelength.

A symmetric W-shaped cavity as illustrated in Fig. 1 is designed for this two-chip VECSEL. In the cavity, the radius of curvature (ROC) of the concaved spherical folding mirror is 30 cm, and the full folding angle is about 15°. The distance between the concaved mirror and the VECSEL chip is around 24 cm, and the highly reflective flat mirror (or flat output coupler) is 4.5 cm away from the VECSEL chip. This cavity configuration defines TEM_{00} mode size on both VECSEL chips: ~ 350 μm diameter (tangential) and ~ 360 μm diameter (sagittal). Two 808 nm pump lasers (not shown in Fig. 1) launch 19.4 W pump power into VECSEL chip 1 and 42.1 W pump power into VECSEL chip 2, respectively. To balance the pump density and match the mode size on both chips, the pump spot size is about 410 μm in diameter on chip 1 and 480 μm on chip 2. The pump spot size on chip 2 is much larger than the mode size, resulting in high-order transverse mode oscillation when pump density is high. The concaved spherical mirror results in a

difference between the tangential and sagittal focal lengths, making the laser beam asymmetric (elliptical). To decrease this asymmetry, the folding angle at the concaved spherical mirror must be kept as small as possible. A tilted plate such as a birefringent filter can be incorporated in the focused region of the cavity, as shown in Table 1, to compensate for the astigmatism due to the nonnormal incidence on the curved mirror. To take advantage of RPG, the folding angle on both chips should be kept as small as possible.

To compare the performance of the single-chip VECSEL and the two-chip VECSEL and to optimize the operation condition for the two-chip VECSEL, before the experiment of two-chip VECSEL, processed VECSEL chip 1 and chip 2 are characterized at 0 °C (heat sink temperature) with a linear cavity (pump spot size, ~ 500 μm diameter; ROC of the output coupler, ~ 30 cm, and cavity length, ~ 21 cm), respectively. The best results are achieved from each VECSEL when the output coupler with the reflectance of 97% is employed. The results are listed in Table 1 and shown in Fig. 2. The lasing wavelength of VECSEL 1 is 3.9 nm shorter than that of VECSEL 2.

To achieve the best performance of the two-chip VECSEL, we have to tune the modal gain peaks of chip 1 and chip 2 such that they overlap, by adjusting the temperature and distribution of the pump power on each chip. During the measurement, the lasing spectrum is monitored by an optical spectral analyzer. We find that the two-chip VECSEL gives the best performance when the lasing spectrum has a narrow linewidth. To extract more output power and delay the thermal rollover, we cool both chips below room temperature (chip 2 is mounted on a −5 °C and chip 1 on a 0 °C heat sink, respectively).

The reflectance of the two output couplers used in our experiments are 95% and 91%. When the 95% output coupler is used in the dual-chip VECSEL, the measured threshold pump power is approximately 5.8 W and the slope efficiency is 0.33. However, when the 91% output coupler is used, the threshold increases to approximately 12 W and the slope efficiency improved to 0.44. Figure 2 shows the output of the two-chip VECSEL as a function of the total absorbed pump power on two chips when the output coupler with 91% reflectance is used. The maximum output power is pump power limited since the pump

Table 1. Comparison of the Best Performance of Single-Chip and Two-Chip VECSELs

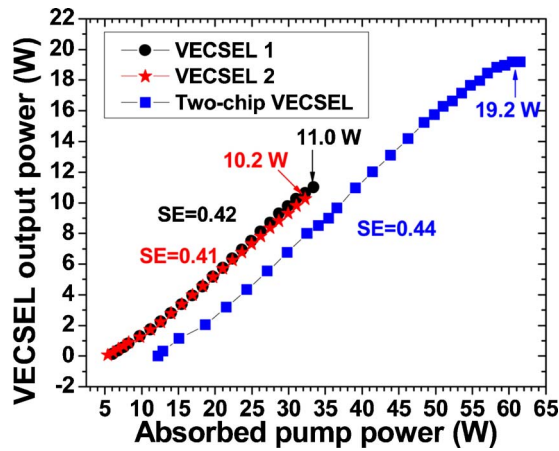| Laser	VECSEL 1	VECSEL 2	Two-chip VECSEL
Threshold pump power (W)	6.13	5.42	12.9
Slope efficiency	0.42	0.41	0.44
Saturated output (W)	11.0	10.2	19.2
Lasing wavelength at the threshold (nm)	963.9	967.8	966.0
M^2 factor at the maximum output	1.75	1.71	2.14

2

Fig. 2. (Color online) Output power of VECSEL 1, VEC-SEL 2, and two-chip VECSEL versus total absorbed 808 nm pump power.
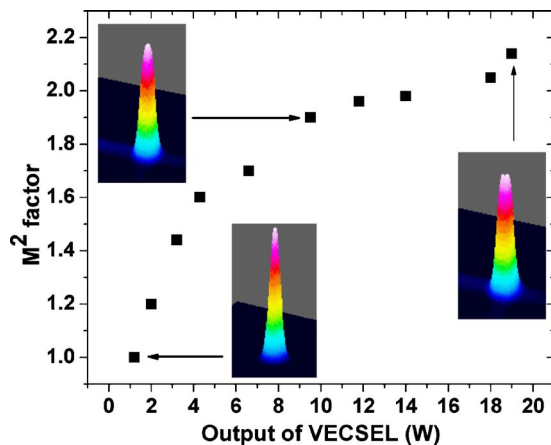

Fig. 3. (Color online) Beam quality factor (M^2 factor) versus the output power of the two-chip VECSEL.

laser for VECSEL chip 1 only provides maximum pump power of 19.4 W. However, due to the unbalanced pump power on both chips (19.4 W pump power on chip 1 and 42 W pump power on chip 2), unavoidable overheat on chip 2 is responsible for the saturation of output power of the two-chip VECSEL.

Figure 3 shows that the beam quality factor (M^2 factor) changes with the increase of output power. The three-dimensional far-field beam profiles are also inserted in Fig. 3. There is degradation in the beam quality. When output power is over 19 W, the laser operates in TEM_{01} mode. This is because the pump spot size is much larger than the mode size. Also, the laser beam is slightly elliptical owing to the folding angle on the concaved spherical mirror. However, the beam quality can be improved by reducing pump spot size on chip 2 such that it matches the TEM_{00} mode size.

If the total pump power of 66 W were to be evenly launched on both chips, the saturation of output power should be avoided, and based on the slope efficiency of 0.44, the output power of the two-chip VECSEL should be over 21 W (see Fig. 2). In comparison with the ideal (lossless) CBC and SBC of two single-chip VECSELs made of chip 1 and chip 2, re-

spectively, where 21 W output power may be achieved by launching total pump power of 66 W (see Fig. 2), the performance of the two-chip VECSEL shows its coherent power scaling advantage over the CBC and SBC of two single-chip VECSELs. Thus the multichip VECSEL can be an efficient coherent power scaling scheme. Similar two-chip optically pumped semiconductor lasers have also been implemented by Coherent Inc.[10]

In summary, we present the development and demonstration of a two-chip VECSEL with over 19 W of output power to prove the concept of the multichip VECSEL. The multichip VECSEL distributes the waste heat on each chip such that more pump power can be launched into VECSEL chips before the laser reaches its thermal rollover. The best performance is achieved when the peak of the modal gain spectrum of each chip is tuned to overlap. The performance of the two-chip VECSEL shows the potential of the multichip VECSEL in coherent power scaling. Consequently, we propose the multichip VECSEL as an efficient coherent power scaling scheme.

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